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Hydrological and Hydrochemical Characteristics of Lakes in the Lena River Delta (Northeast-Siberia, Russia)

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Abstract: This study investigates a variety of lakes of different origin in the Siberian Lena River delta for lake hydrological, hydrochemical, and morphometric characteristics. The results are based on *in-situ* field measurements and subsequent water sample analyses. Significant differences between the characteristics of polygonal ponds, thermokarst and oxbow lakes, and lakes influenced by sea-water are revealed. The differences in hydrochemical characteristics are explained by differences in the lakes' specific locations and relief settings, hydrological regimes, and origins.

Zusammenfassung: Diese Studie beschreibt eine Reihe von Seen unterschiedlicher Entstehung im Deltagebiet der Lena (Sibirien) in Hinsicht auf ihre hydrologischen, hydrochemischen und morphologischen Charakteristika. Die Ergebnisse basieren auf *in-situ* Feldmessungen und nachfolgenden Wasseranalysen. Es zeigen sich deutliche Unterschiede zwischen Polygonseen, Thermokarst- und Altwasserseen sowie Seen mit Einfluss von Meerwasser. Die Unterschiede der hydrochemischen Charakteristika der Seen lassen sich mit ihrer spezifischen Lage, den Reliefstrukturen, der hydrologischen Regime und Entstehung erklären.

INTRODUCTION

The circumpolar coast of the Arctic is characterized by numerous river deltas rich in lakes. These are regions with rapidly changing climatic conditions (AMAP 2012). Arctic lakes play an important role in affecting territorial climates and air mass transfer processes. At the same time, climatic variations affect the properties of many Arctic water features. Arctic rivers and large lakes adapt to changes over long periods of time, and the effects caused by changes in their regimes might become obvious only in the future. The reaction of small objects like polygonal ponds and thermokarst lakes to climatic variations is more rapid. Therefore, investigations of the small water bodies become important for understanding water and chemical components cycles.

The river delta lakes are influenced by the rivers especially during spring floods. The river input of inorganic nutrients to lake waters and impact on the regime of phytoplankton and zooplankton communities in the lakes is most pronounced at the beginning of the ice-free season. The degree of this influence and the timing of interaction between river and lake waters in delta areas depend on the lake elevation relative to the river water level (Spears & Lesack 2006).

Climate, soil, and landscape features control the hydrological and hydrochemical conditions of tundra landscapes. In spring, rapid and intensive snowmelt occurs while the soil is still frozen, promoting the spread of water and chemical elements throughout the landscape. Surface ice enriched with dissolved substances melts and the meltwater spreads across the tundra, creating hydrochemically uniform conditions. After spring floods are done, individual polygonal ponds become separated from each other and do not have a strong hydrological connection; local factors such as thawed soil waters, thermokarst processes, vegetation, and evaporation play a crucial role in changing hydrochemical characteristics (Thompson & Woo 2009).

Thermokarst is an important phenomenon in Arctic regions and particularly in the big river deltas. Thermokarst processes affect hydrological conditions and the hydrochemistry (major and trace element enrichment) of water bodies. Major ions and trace elements are released from frozen sediments of disturbed (thermokarst-affected) areas and are transported to lakes via surface fluxes, increasing the concentration of major ions in the lake water compared to lakes located in undisturbed areas (Chagu'e-Goff & Fyfe 1997, Kokelj et al. 2005, Thompson & Woo 2009).

Studies of paleolimnological and palynological aspects of lake ecosystems in Canada, in the USA, in Greenland, on the North Atlantic Islands, and in the Russian Arctic are summarized in Pienitz et al. (2004). The characteristics of aquatic vegetation, the physical and chemical properties of bottom sediments, the isotopic composition of lake systems, and problems of water pollution and bottom sediments of lakes are considered by Pienitz et al. (2004).

Prior to the present study thermokarst lakes in the Lena River delta had been little investigated. Hydrochemical study was concentrated on the lakes and polygonal ponds of Samoylov Island (Wetterich et al. 2008a, Abnizova et al. 2012, Chetverova et al. 2013). Thermal processes in thermokarst lakes are discussed in Boike et al. (2015a). Based on the results of the latest studies available at that time, the main morphometric and hydrochemical characteristics of lakes in the northern rivers of Yakutia (including six lakes in the downstream part of the Lena River catchment) were studied by Gorodnichev et al. (2014). According to this study, lake waters are characterized by low concentrations (less than 200

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mg L^{-1}) of total dissolved solids (TDS) and calcium (Ca) or magnesium (Mg), and bicarbonate (HCO_3^-) dominates. Lake water transparency (Secchi disc visibility) reaches 3.45 m. Lakes in the downstream part of the Lena River catchment are characterized by high pH values of 7.9 to 9.6, while lakes of the Lena River delta have pH values of 6.7 to 7.7.

The main objective of the current research is to investigate a variety of lakes of different types in the Lena River delta for their hydrological and hydrochemical characteristics and to relate processes taking place in the Lena River delta to the spatial and temporal (seasonal) variability of lake hydrochemical parameters.

STUDY AREA

The Lena River delta is the largest delta in the Arctic. The aquatic system of the Lena River delta includes more than 800 branches with a total length of about 6,500 km. The total Lena delta area according to the latest estimations is 29,000 km^2 (Morgenstern et al. 2011a). Because of climatic, hydrological, and permafrost conditions more than 30,000 lakes (Bolshiyanov et al. 2013) of different forms and sizes have formed in the delta. Most of the lakes are relatively small in size, with areas that do not exceed 10 km^2. About 73 % of these lakes are located in the western part of the delta. Only ten lakes have a surface area of more than 10 km^2. Large lakes (>10 km^2) are also mostly located in the western part of the delta, whereas the eastern part is characterized by a prevalence of lakes formed by fluvial processes and by oxbows (Bolshiyanov et al. 2013).

This area of the Lena River delta is characterized by three geomorphological main terraces (Grigoriev 1993, Schwamborn et al. 2002). The first terrace exists at elevations between 0 and 10 m above sea level (a.s.l.) and includes the active floodplain; it is of Holocene age and represents the modern river delta with high fluvial activity. The first terrace occupies most of the eastern Lena delta-area in between the second and third terraces, which are remnants of Pleistocene accumulation plains (Schwamborn et al. 2002). The second terrace, which occupies the northwestern Lena River delta at elevations between 20 and 30 m a.s.l., formed during the late Pleistocene and early Holocene and is characterized by sandy fluvial deposits with low ice content (Schirrmeister et al. 2011a). The third terrace is comprised of several islands in the southern delta with elevations of up to 66 m a.s.l. and is composed of late Pleistocene ice-rich permafrost deposits (Yedoma-type Ice Complexes) underlain by fluvial sands and a Holocene cover (Wetterich et al. 2008b, Schirrmeister et al. 2011b). Polygonal tundra is widespread on all river terraces; however, it is most prominent on the first geomorphological main terrace. The different geneses, deposit types, and relief-forming processes of the three geomorphological main terraces cause differences in their predominant lake types (Morgenstern et al. 2008). The first terrace features a high density of small water bodies, mainly polygonal ponds and small thermokarst and oxbow lakes. On the second terrace, large elongated thermokarst lakes occur and on the third terrace thermokarst lakes prevail that are often situated in partially drained deep basins (alasses).

The studied lakes presented in this article are situated on the Holocene river terrace of the first geomorphological main terrace, in the coastal zone of the second geomorphological main terrace, on the third main terrace and on the downstream part of the Lena River catchment (Fig.1). They can be grouped into four lake types.

Polygonal ponds

The study of Muster et al. (2012) shows that small water bodies such as ice-wedge polygonal ponds with depth of 0.5-1 m and smaller than 0.1 ha (1,000 m^2) surface area are prevalent in the study region, while thermokarst lakes larger than 10 ha represent only 1 % of the total number of Lena Delta lakes. A total of about 6,200,000 polygonal ponds i.e. 748 polygonal ponds per square kilometer exist here. In contrast to large lakes, polygonal ponds mostly occur on the first main terrace and are concentrated in the central and eastern parts of the delta (Muster et al. 2012).

Polygonal ponds are a main feature of polygonal tundra; polygonal tundra represents a specific type of Arctic landscape and covers a large part of the Lena River delta area, especially on the Holocene river terraces of the first geomorphological main terrace and in drained lake basins of the third geomorphological main terrace. Polygonal ponds that form in the centre of low-centred polygons are usually shallow and have rounded or square shapes (Fig. 2a, 2b) while polygonal ponds that develop along the ice-wedge network of high-centred polygons have more irregular outlines. Erosional and thermokarst processes deepen and enlarge polygonal ponds; over time, several polygonal ponds can unite to form one lake (Fig. 3a). Thermokarst processes begin to prevail during the next stage of lake formation.

Thermokarst lakes

Thermokarst lakes are widespread within all three terraces of the delta (Are & Reimnitz 2000). We observed small and shallow thermokarst lakes (up to 8 m deep) on the first and the third geomorphological main terraces of the Lena River delta. The study of Are & Reimnitz (2000), however, indicates that Arga Island is characterized by relatively large lakes with hollows in the center of the lake bed up to 25 m deep.

Thermokarst is defined as the process by which the surface subsides and lakes and depressions form due to thawing of ice-rich permafrost or the melting of ground ice (van Everdingen 2005). These processes have been occurring throughout the Lena River delta and have led to the formation of numerous lakes, which are fed by melt waters and atmospheric precipitation (Fig. 4a, 4b). Lakes on the first terrace formed mostly via the coalescence of polygonal ponds. Lake 5 on Samoylov Island is a good example of a combination of these two processes, or a transitional stage from a polygonal to a thermokarst type of lake. Thus, thermokarst processes influence most of Lake 5, which is deep and has a smooth contour line (Fig. 3b). However, in the western part of Lake 5, another process is prevalent. Polygons are still coalescing in this area, and this part of the lake is shallow with a rough contour line. Some of the lakes on the first terrace have v-shaped profiles

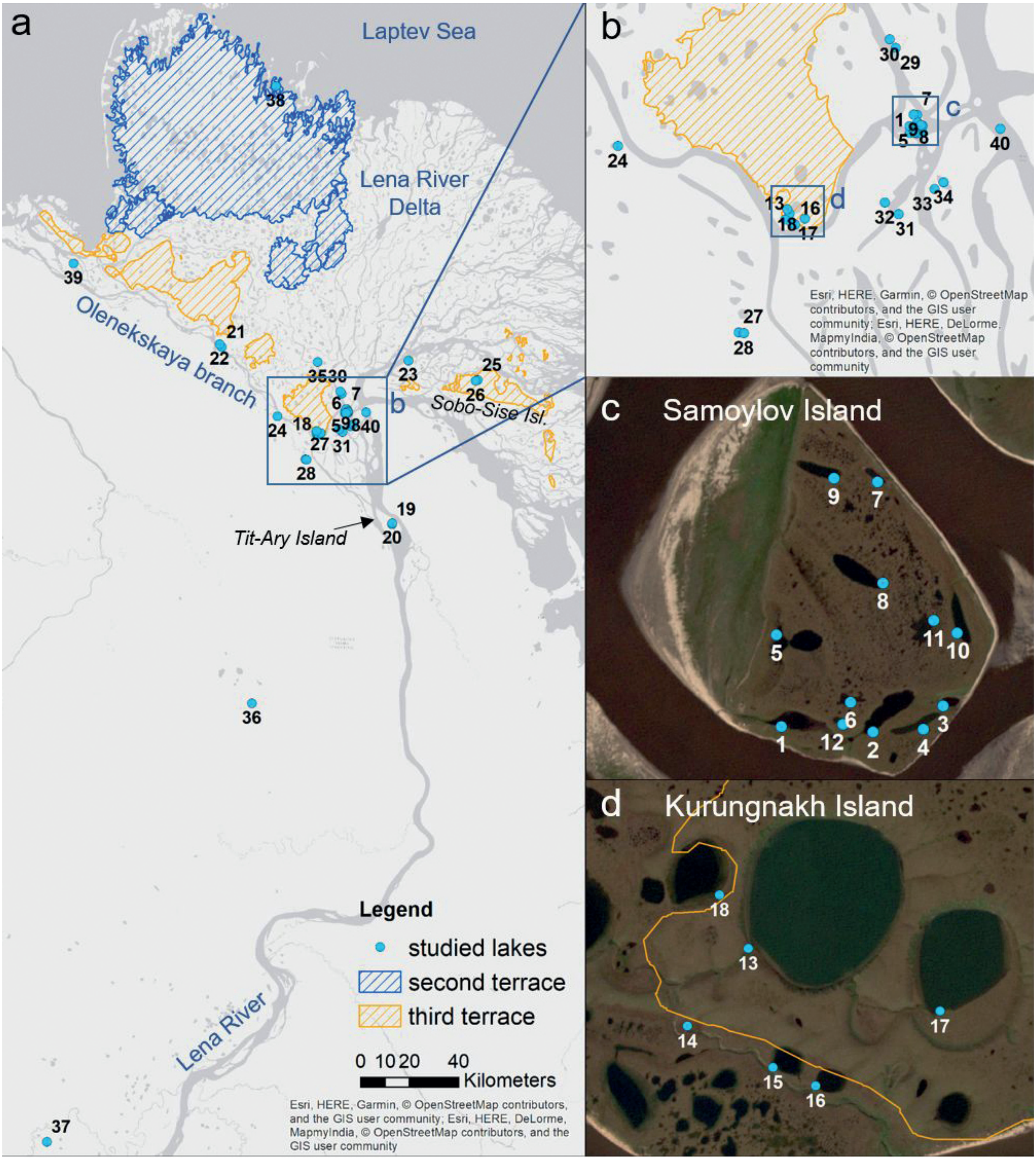

Fig. 1: Studied water bodies in the Lena River delta (The Lena River terraces as described by MORGENSTERN et al. 2011b).

Abb. 1: Untersuchte Gewässer im Unterlauf der Lena und im Lena-Delta auf der Samoylov Insel und Kurungnakh Insel; vgl. auch Tab. 1; Darstellung der Lena-Terrassen wie bei MORGENSTERN et al. 2011b).

rather than flat bottoms (BOIKE et al. 2013). Thermokarst lakes of the third geomorphological main terrace are larger in size and deeper than those on the first terrace. They are major components of the ice-rich permafrost landscape of the third terrace and formed between 13 and 12 ka BP (MORGENSTERN et al. 2011a, 2013a). In our study, we investigated third terrace lakes on Kurungnakh and Sobo-Sise islands (Fig. 1).

Oxbow lakes

These water bodies represent an abandoned meander or stream part that has become isolated from the river channels. In the Lena River delta, oxbows are located on the flood plain and on the Holocene river terrace. This lake type is characterized by an elongated shape and has connections with the Lena River

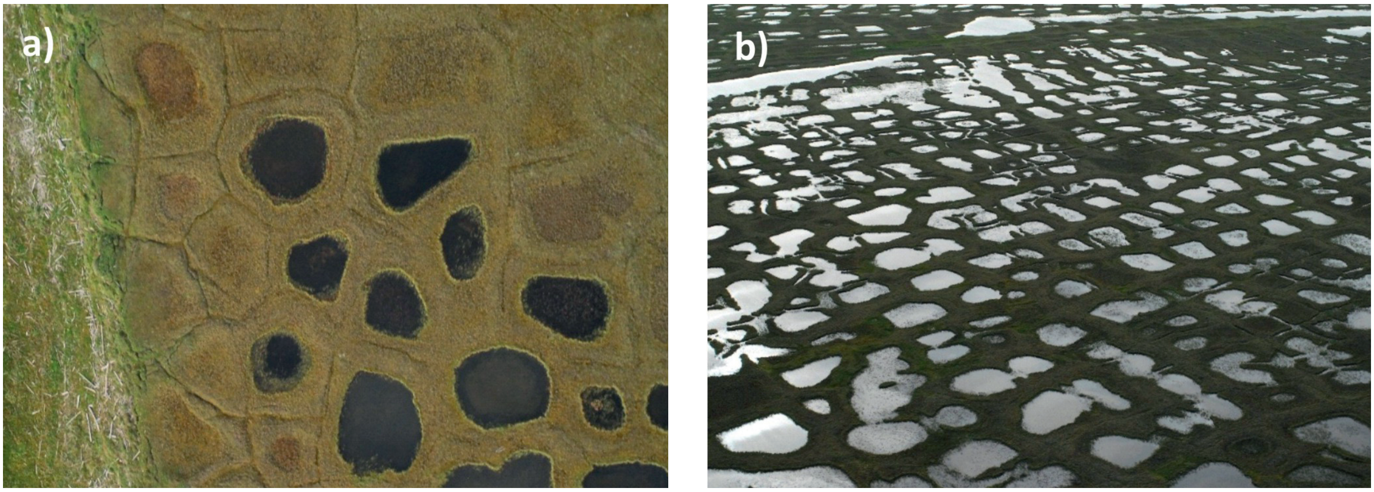

Fig. 2: Polygonal ponds on (a) Samoylov Island and on (b) Sobo-Sise Island in the Lena River delta; photo by A. Chetverova 2014.

Abb. 2: Polygonseen im Lena-Delta auf der Samoylov Insel (a) und der Sobo-Sise Insel (b); vgl. Abb. 1 und Tab. 1 (Foto: A. Chetverova 2014).

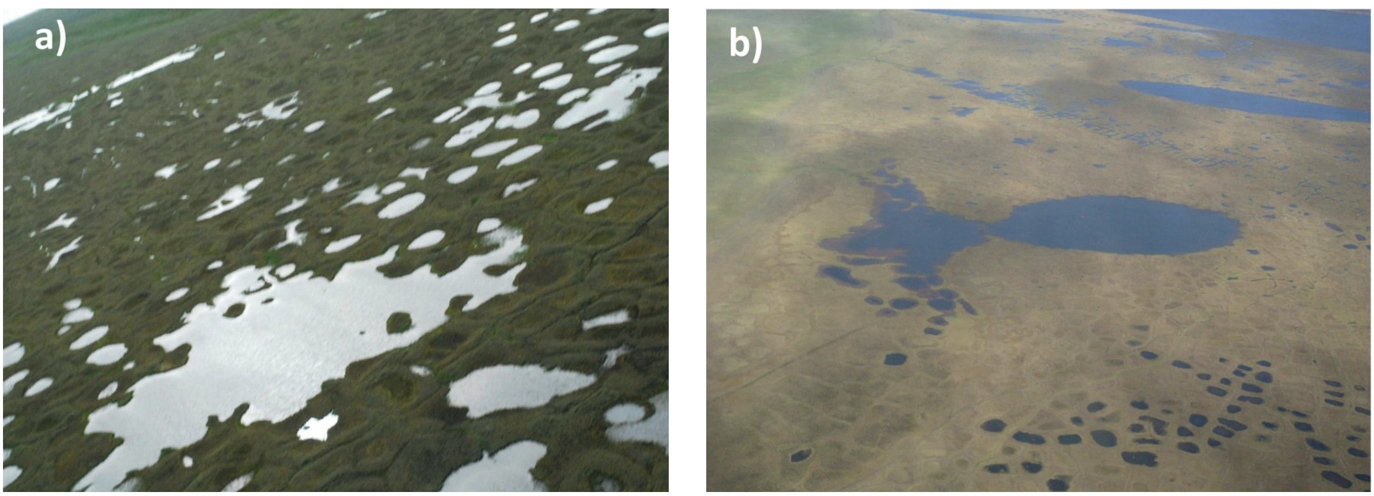

Fig. 3: Polygonal Lake 11 (a) and the polygon coalescence process occurring at thermokarst Lake 5 on (b) Samoylov Island, (photo by A. Chetverova).

Abb. 3: (a) Polygonsee 11 und der Prozess der Polygonverbindung am Beispiel des Thermokarstsees 5 (b) auf der Samoylov Insel (Foto: A. Chetverova).

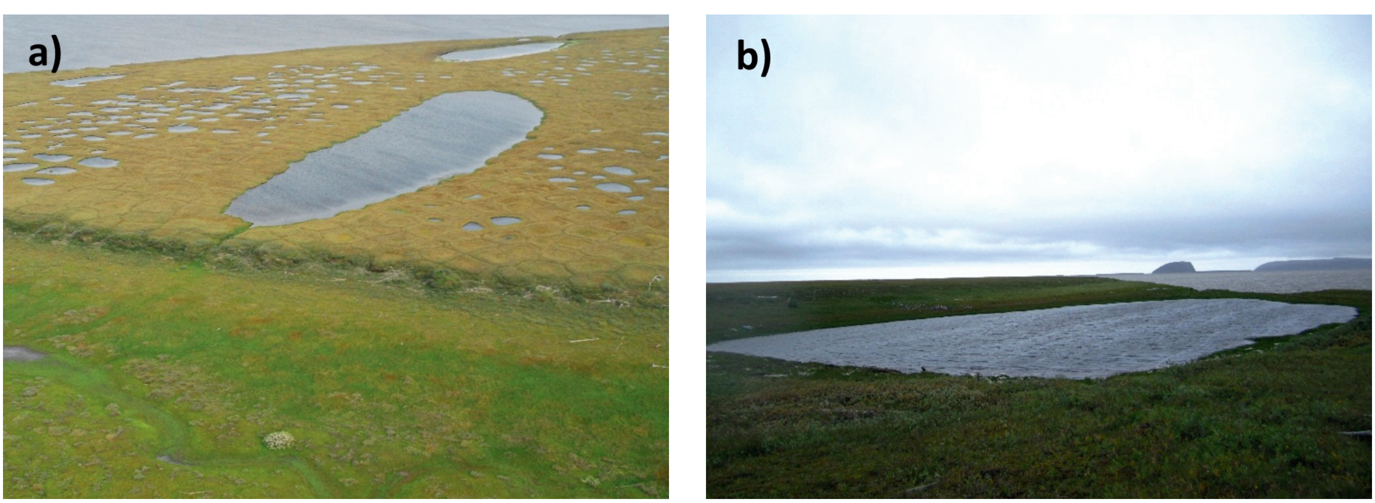

Fig. 4: Typical thermokarst lakes: (a) Lake 9 in the foreground and Lake 7 (see Fig. 1c), and (b): Lake 33 (see Fig. 1b), (photos by A. Chetverova, 2012).

Abb. 4: Typische Thermokarstseen, (a) See 9 im Vordergund und See 7 im Hintergrund (vgl. Abb. 1c); (b) Thermokarstsee 33 im zentralen Lena Delta (vgl. Abb. 1b) (Fotos: A. Chetverova 2012).

waters during the spring flood. Oxbow lakes of the delta vary in depth from 3-4 m to more than 10 m because thermokarst processes are actively deepening these lakes.

Lagoon lakes

These lakes are located on the edge of the subaerial delta and are characterized by an active marine influence and by specific hydrochemical conditions.

MATERIAL AND METHODS

Regular investigations of Lena River delta lakes have been conducted since 1998 under the framework of the Russian-German "Lena" Expeditions. All data presented in this paper were collected during field seasons of 2005 and 2009 to 2013. As a result of limnological investigation, morphometric and hydrochemical parameters of the different water bodies have been collected.

Morphometric parameters

Morphometric parameters of the lakes (water depth and shoreline coordinates) were measured by a portable Garmin GPSMap 420 Echo Sounder installed on a rubber boat. Depth profiles were determined by measurements made in a zigzag line while the boat travelled in the direction of the longest part of the lake.

Bathymetry schemes were created by the authors and are available for most of the lakes on Samoylov Island and some lakes on Kurungnakh Island in the PANGAEA database (Morgenstern et al. 2013b, Boike et al. 2015b).

Water sampling

Water samples were taken from the lakes with different periodicities. Water samples from most of the lakes were taken only once during a summer season. Samoylov Island lakes were sampled several times during each summer season (two or three times per month). Water temperature (T), dissolved oxygen (O_2), and pH were measured *in-situ* using portable sensors (WTW multi 340i) in surface water and within the depth profile in the Samoylov Island lakes (Lake 1, Lake 2, Lake 4, and Lake 7). These lakes were well mixed and were not stratified at the time of sampling due to wind induced mixing.

Water samples were filtered through a cellulose acetate (CA) filter, 0.45 μm pore size. For major and trace element determination water samples were collected, stored, and transported in 20-60 ml plastic bottles pre-cleaned by nitric acid (HNO_3) (1:1 diluted HNO_3). Water samples for cations were acidified in the field with 50-100 μl of 65 % HNO_3.

Laboratory analysis

All samples were processed in the Russian-German Otto-Schmidt Laboratory for Polar and Marine Research (OSL) in the Arctic and Antarctic Research Institute (AARI, St. Petersburg) and in the analytical laboratory of the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI, Potsdam). Major ion concentrations in the water samples were measured using an ion chromatograph (IC), a 761 Compact IC (Metrohm, detection limit: 0.1 mg L^{-1}). An Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES), a CIROS VISION ICP-OES (Spectro, detection limit: 0.001-0.2 mg L^{-1}), was used to measure trace element concentrations. The possible errors of anylysis did not exceed ±5 %.

Laboratory analysis of water samples revealed the concentrations of the major ions: calcium (Ca^{2+}), potassium (K^+), magnesium (Mg^{2+}), sodium (Na^+), chloride (Cl^-), sulfate (SO_4^{2-}) and hydrogen carbonate (HCO_3^{2-}) and also a variety of trace elements (aluminium (Al), boron (B), barium (Ba), bromine (Br), cadmium (Cd), cobalt (Co), copper (Cu), iron (Fe), mercury (Hg), lithium (Li), manganese (Mn), molybdenum (Mo), nickel (Ni), phosphorus (P), lead (Pb), silicon (Si), strontium (Sr), titanium (Ti), zinc (Zn)). The TDS value was accepted as the sum of the major ion concentrations.

Statistical analysis

Descriptive statistical analysis, significance tests, and Box-Whisker plots for hydrochemical variables were produced using IBM SPSS statistics software (version 23.0). Tests of differences in the mean were conducted with the non-parametric Mann Whitney U-test which is suitable for hydrochemical data when the data are non-normally distributed and for small sample units ($n \geq 3$) (Sokal & Rohlf 1995).

The descriptive statistical analysis revealed distinctly higher values in Lake 39 for all hydrochemical variables compared to all other lakes; therefore, we decided to analyze and to present the hydrochemical characteristics of Lake 39 separately.

The hydrochemical characteristics of different lake types are presented compared to the river and pore water samples. The hydrochemical composition of the Lena River delta is presented for the cross section of the main Lena River delta-branch (126.7357 E, 72.3749° N) and includes summer data from 2010-2013. Tundra pore waters from the active layer of peat sediments were sampled randomly in different parts of Samoylov Island.

RESULTS

Morphometrical and hydrological lake characteristics

The basic characteristics of the 39 lakes included in this study are given in Table 1. The lakes are small in size and not very deep; they differ in shape. None of the studied lakes has a surface area > 0.1 km^2.

Lake No	Latitude	Longitude	Area	Year of study	Area, (km²)	Depth (av/max) (m)	Geomorpho-logical setting	Type of lake
1	72.3684° N	126.4827° E	Samoylov Isl.	2009-2012	0.032	2.1 / 5.2	1st	Oxbow
2	72.3683° N	126.5017° E	Samoylov Isl.	2009-2012	0.048	6.5 / 16.3	1st	Oxbow
3	72.3701° N	126.5159° E	Samoylov Isl.	2009-2012	0.009	3.3 / 6.3	1st	Oxbow
4	72.3686° N	126.5120° E	Samoylov Isl.	2010-2012	0.020	1.8 / 3.6	1st	Thermokarst
5	72.3741° N	126.4809° E	Samoylov Isl.	2009-2012	0.049	3.8 / 12.7	1st	Thermokarst
6	72.3701° N	126.4968° E	Samoylov Isl.	2009, 2012	n/a	- /3.5	1st	Polygonal
7	72.3839° N	126.5004° E	Samoylov Isl.	2009-2012	0.006	1.5 / 2.7	1st	Thermokarst
8	72.3776° N	126.5024° E	Samoylov Isl.	2010-2012	0.042	2.6 / 6.2	1st	Thermokarst
9	72.3840° N	126.4914° E	Samoylov Isl.	2009-2012	0.021	2.5 / 4.8	1st	Thermokarst
10	72.3747° N	126.5181° E	Samoylov Isl.	2009-2011	0.022	2.0 / 4.1	1st	Thermokarst
11	72.3754° N	126.5132° E	Samoylov Isl.	2010-2012	0.026	1.0 / 3.1	1st	Polygonal
12	72.3687° N	126.4954° E	Samoylov Isl.	2012	n/a	- /2.0	1st	Polygonal
13	72.2955° N	126.1576° E	Kurungnakh Isl.	2014	n/a	n/a	3rd	Thermokarst
14	72.2901° N	126.1450° E	Kurungnakh Isl.	2014	n/a	n/a	1st	Thermokarst
15	72.2876° N	126.1643° E	Kurungnakh Isl.	2014	n/a	n/a	1st	Thermokarst
16	72.2865° N	126.1739° E	Kurungnakh Isl.	2014	n/a	n/a	1st	Thermokarst
17	72.2919° N	126.2006° E	Kurungnakh Isl.	2014	n/a	n/a	3rd	Thermokarst
18	72.2990° N	126.1507° E	Kurungnakh Isl.	2014	n/a	n/a	1st	Thermokarst
19	71.9721° N	127.0966° E	Tit-Ary Isl.	2010, 2012	n/a	n/a	3rd	Thermokarst
20	71.9680° N	127.0902° E	Tit-Ary Isl.	2010, 2012	n/a	n/a	1st	Oxbow
21	72.5856° N	124.9413° E	Chay-Ary	2005	n/a	n/a	3rd	Thermokarst
22	72.5961° N	124.9144° E	Chay-Ary	2005	n/a	- /2.0	3rd	Thermokarst
23	72.5700° N	127.2298° E	Sardakh Isl.	2012	n/a	n/a	3rd	Thermokarst
24	72.3453° N	125.6693° E	Chay-Tumus	2005	n/a	- /8.0	river catchment	Thermokarst
25	72.5044° N	128.0789° E	Sobo-Sise Isl.	2014	n/a	n/a	3rd	Thermokarst
26	72.5013° N	128.0541° E	Sobo-Sise Isl.	2014	n/a	n/a	3rd	Thermokarst
27	72.1928° N	126.0314° E	Southwestern edge of the delta	2012	n/a	n/a	river catchment	Thermokarst
28	72.1925° N	126.0468° E	Southwestern edge of the delta	2012	n/a	n/a	river catchment	Thermokarst
29	72.4398° N	126.4327° E	Central Delta	2012	n/a	n/a	1st	Thermokarst
30	72.4467° N	126.4157° E	Central Delta	2012	n/a	n/a	1st	Thermokarst
31	72.2993° N	126.4616° E	Central Delta	2012	n/a	n/a	1st	Thermokarst
32	72.3085° N	126.4213° E	Central Delta	2012	n/a	n/a	1st	Thermokarst
33	72.3218° N	126.5580° E	Central Delta	2012	n/a	n/a	1st	Thermokarst
34	72.3278° N	126.5827° E	Central Delta	2012	n/a	n/a	1st	Thermokarst
35	72.5516° N	126.1238° E	Central Delta	2011	n/a	n/a	1st	Thermokarst
36	71.2889° N	125.5611° E	Downstream	2010	n/a	1.4 / 10.5	river catchment	Thermokarst
37	69.6322° N	123.6651° E	Downstream	2010	n/a	3.2 / 4.9	river catchment	Thermokarst
38	73.5525° N	125.4140° E	Northern edge of the delta	2005	n/a	n/a	2nd	Lagoon
39	72.8463° N	123.0330° E	Olenekskaya branch mouth	2012	n/a	n/a	1st	Thermokarst

Tab. 1: Location, morphometric parameters, and classification of studied lakes.

Tab. 1: Lage, morphologische Parameter und Klassifizierung der untersuchten Seen.

Thermokarst lakes

The majority of investigated lakes are thermokarst lakes (Tab. 1). Typical delta thermokarst lakes were investigated on the first and the third geomorphological main terraces of the Lena River delta, on Samoylov, Kurungnakh, Tit-Ary, Chay-Ary, Sardakh, Chay-Tumus, and Sobo-Sise islands. The depths of investigated thermokarst lakes reached 8 m (Lake 24).

Some of the thermokarst lakes of Samoylov Island (Lakes 5, Lake 7, Lake 9, and Lake 10) and lakes located on the first terrace of Kurungnakh Island (Lake 14, Lake 15, and Lake 16) are influenced by the river water (in particular by Olenekskaya branch water) and can be flooded during extremely high spring runoff.

Thermokarst lake temperatures are affected by permafrost and by active layer melt water. These influences provide a cooling effect, the extent of which depends on lake volume. Thus, water temperatures during summer seasons (June to August) increased. The average water temperature was 5 °C at the beginning of the summer and 13 °C at the end of the summer. Relatively big and deep lakes are characterized by thermal stratification with phases of complete mixing.

Delta lakes, including thermokarst lakes, experience a long ice-covered period from the middle of October until June breakup. Floating ice pieces may be observed until the beginning of July. Ice-cover thickness measured on Lake 5, Lake 8, Lake 9, and Lake 10 of Samoylov Island in 2013 reached 2.4-2.5 m; ice thickness on Lake 14, Lake 15, Lake 16, Lake 17, and Lake 18 of Kurungnakh Island was 2.2-2.4 m.

Some of the thermokarst lakes are located outside of the Lena River delta catchment. Lake 27 and Lake 28 are located on the southeast delta edge and Lake 36 and Lake 37 are found in the downstream part of the Lena River catchment.

Lake 37 (Kutyunda Lake, Biskaborn et al. 2016) and Lake 36 (Elgene-Kuele Lake, Biskaborn et al. 2013, Schleusner et al. 2015) are thermokarst lakes located outside of the delta in the downstream part of the Lena River catchment and were compared with delta lakes. In contrast to the delta lakes the Kutyunda and Elgene-Kuele lakes are relatively big in size (4.9 km^2 and 1.4 km^2 respectively). Lake 37 is of tectonic origin and has been influenced by thermokarst processes. This lake is located in the taiga zone and is not affected by spring flooding, e.g. it is situated on the second river terrace of the left Lena tributary and has a maximal depth of 3.2 m (Vakhrameeva et al. 2011).

Lake 36 is located in the south taiga zone. The maximal depth of 10.5 m was measured in the northern part of the lake. The lake basin formed under thermokarst processes of ice-complex deposits, which are intensively degraded, forming deep thermo-abrasive niches (Vakhrameeva et al. 2011).

Polygonal ponds

We observed small polygonal ponds and bigger lakes made up of coalesced polygonal ponds which are widespread within the delta. The polygonal ponds could be as deep as 3.5 m (Lake 6), whereas the depth of the coalesced polygonal pond on Samoylov Island (Lake 12) did not exceed 2 m. This observed difference can be explained by differences in the intensity of the thermokarst processes. The water temperatures of small polygonal ponds reached 23 °C. The water columns of small, shallow polygonal ponds are well mixed. The ice-cover thickness measured in 2013 was as thick as 2.3 m; thus, small Samoylov Island ponds and probably water bodies in other parts of the delta can freeze completely in winter.

Oxbow lakes

Typical oxbow lakes were studied on Samoylov (Lake 1, Lake 2, and Lake 3) and on Tit-Ary (Lake 19) islands. Oxbow lakes on Samoylov Island are characterized by their elongated shapes, and they are the deepest lakes observed in the delta.

Lake 1 and Lake 3 are influenced by river water every year during the spring flood, whereas Lake 2 is only flooded in years with extremely high spring water levels. A study of Samoylov Island lakes during different seasons shows that Lake 1 and Lake 3 are annually flooded in May and become disconnected from the river when the peak flood has passed. Lake 2 is located further from a river and is deeper than Lake 1 and Lake 3, with small depressions (hollows) on the bottom. The maximum depth of Lake 2 is 16.3 m; this is the maximum observed depth among all investigated lakes. These depressions or hollows are much deeper compared to the general lake floor and in our opinion show evidence of thermokarst process development.

Lake 3 presents a very specific example of lake-river water interaction. This lake is annually flooded by river water during the spring freshet; it also can be occasionally connected with Olenekskaya branch water during all open water periods as a result of splashes during stormy weather. The ice-cover thickness measured in 2013 was as deep as 2.4 m.

Lagoon lake

Lagoon Lake 38 is situated close to Kuba Bay and is connected to the Bay by a narrow strait; the shape of this lake is typical for lagoons.

Hydrochemical Characteristics of Water Bodies

The hydrochemical characteristics of the majority of the lakes presented in this paper were determined during the summer season (July–August). In summer, lake water in the Lena River delta in general can be characterized by a low TDS concentration not exceeding 160 mg L^{-1}, neutral to slightly alkaline pH (6.7-7.7), and negligible concentrations of minor and trace elements; most were below the detection limits of our methods. All the lakes were typically well oxygenated. Nevertheless, a wide range in concentrations of Si^{4+} (0.12 to 1.83 mg L^{-1}), Sr^{2+} (0.02 to 0.26 mg L^{-1}), Fe^{3+} (<0.01 to 0.6 mg L^{-1}), Ba^{2+} (<0.005 to 0.029 mg L^{-1}), and B^{3+} (<0.2 to 3.53 mg L^{-1}) were measured in waters of the investigated lakes.

Waterbody type	n	Statist. param.	Ca mg L^{-1}	Mg mg L^{-1}	Na+K mg L^{-1}	Cl mg L^{-1}	SO4 mg L^{-1}	HCO3 mg L^{-1}	TDS mg L^{-1}	Si mg L^{-1}	Sr mg L^{-1}	Ba mg L^{-1}	Fe mg L^{-1}
Oxbow lakes	21	Av	11.6±0.73	3.87±0.19	5.65±0.40	6.79±0.77	4.08±0.46	52.1±2.99	84.1±4.58	0.76±0.09	0.08±0.005		
		range	7.67-23.9	3.07-7.35	2.09-8.63	1.01-12.3	0.41-7.95	38.8-105	60.4-160	0.2-1.83	0.04-0.15	<0.005-0.015	<0.01-0.052
		C_v	0.29	0.23	0.33	0.52	0.52	0.26	0.25	0.56	0.30		
Thermokarst lakes	56	Av	8.85±0.50	4.24±0.22	2.35±0.18	2.89±0.34	1.64±0.19	47.0±2.54	66.9±3.45	0.57±0.05	0.05±0.04		
		range	2.55-19.5	0.6-8.04	0.3-7.03	0.5-14.1	0.2-7.78	13.7-92.2	20.8-134	0.13-1.52	0.02-0.23	<0.005-0.024	<0.01-1.38
		C_v	0.42	0,39	0,56	0,89	0,88	0,40	0,39	0,62	0,57		
Lake 39	1		28	21,7	172	335	2,39	72	631	0.18	0.24	0,029	0.011
Polygonal lakes	9	Av	8.06±0.86	4.94±0.46	1.71±0.11	1.68±0.22	0.85±0.11	47.9±5.44	70.8±6.83	0.47±0.1	0.05±0.004		
		range	5.60-13,7	3.6-8.0	1.4-2.5	0.8 - 2.51	0.2-1.16	26.6-82.0	48.4-110	0.12-1.48	0.02-0.07	<0.005	<0.01-0.60
		C_v	0.32	0.28	0.18	0.40	0.40	0.34	0.30	0.81	0.36		
Lake 38	1		23.0	45.5	468	816	88.0	25,2	1466	n.a.	0.26	n.a.	n.a.
Lena River	18	Av	17±0.38	4.33±0.11	7.92±0.76	7.6±0.96	11.5±1.27	66.4±4.06	114.8±4.46	2.22±0.07	0.14±0.006	0.012	
		range	14.2-20.4	3.58-4.94	4.39-13.6	0.43-13.6	0.16-20.1	52.2-116	94.9-154	1.79-2.73	0.1-0.18	0.016-0.021	<0.01-0.05
		C_v	0.09	0.11	0.41	0.54	0.47	0.26	0.17	0.14	0.18		
Pore waters	9	Av	14.7±1.82	7.68±1.29	2.48±0.4	2.55±0.40	1.40±0.07	83.1±11.7	98.7±13.6	1.80±0.33	0.09±0.01		
		range	7.10-23.2	2.59-15.8	1.37-4.28	1.10-4.97	1.11-1.72	39.4-150	46.7-173	0.73-3.01	0.04-0.17	<0.005-0.015	<0.01-2.79
		C_v	0.39	0.54	0.41	0.51	0.15	0.45	0.45	0.53	0.48		

Tab. 2: Hydrochemical characteristics of water bodies of the Lena River delta and the downstream part of the Lena River catchment. Note Av: average±standard error; range: minimum - maximum value; C_v: variance.

Tab. 2: Hydrochemische Charakteristika der Gewässer im Lena-Delta und Unterlauf des Lena-Einzuggebietes. Statistische Parameter Av: Durchschnitt±Standardfehler; range: Minimum - Maximumwert; C_v: Varianz.

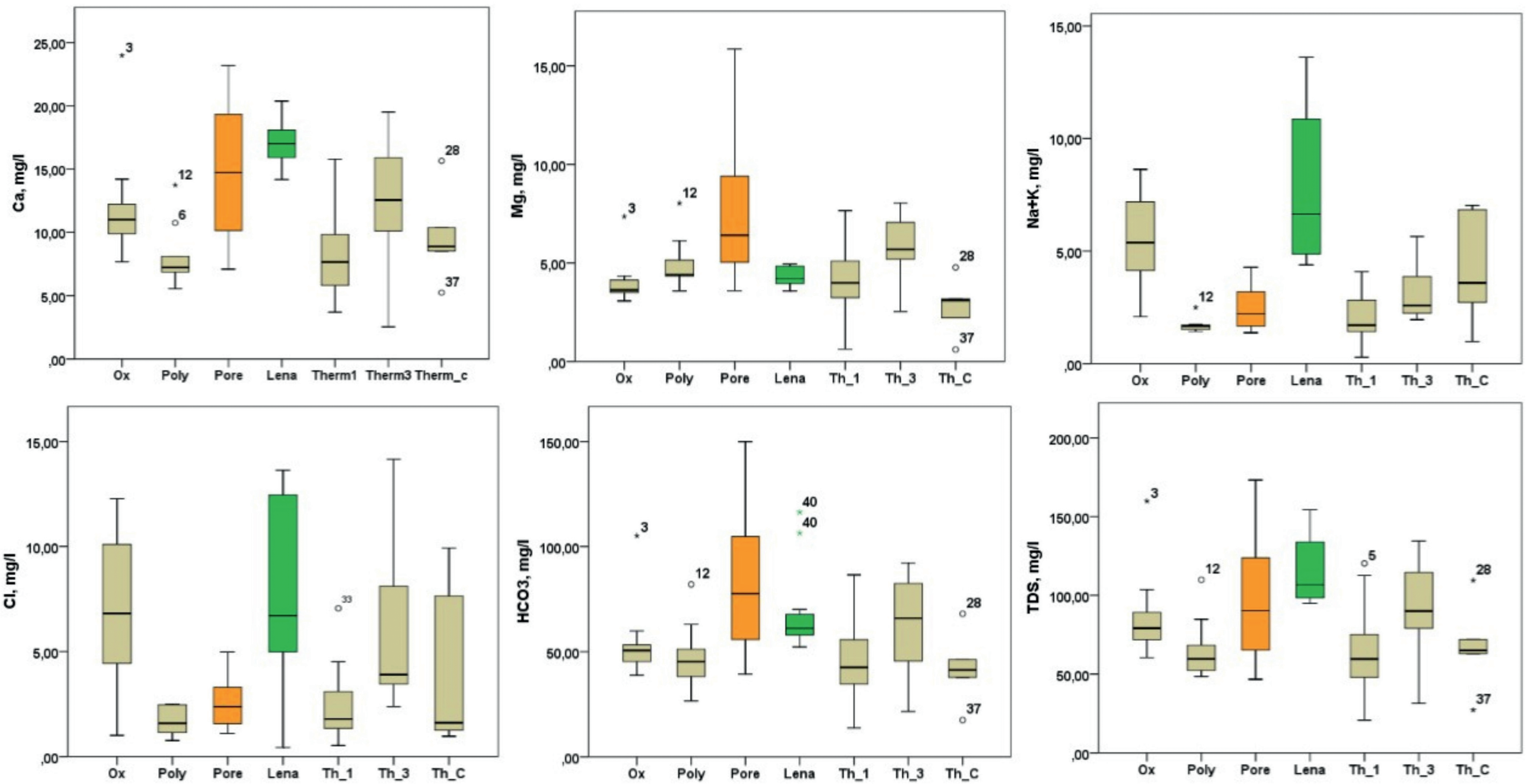

Fig. 5: Box-Whisker plots for selected hydrochemical characteristics categorized according to the water body types. Ox: oxbow lakes (n = 21); poly: polygonal ponds (n = 9); Pore: pore waters (n = 9); Lena: Lena River (n = 18); Therm1 (Th_1): thermokarst lakes of 1st terrace (n = 44); Therm3 (Th_3): thermokarst lakes of 3rd terrace (n = 7); Therm_c (Th_c): thermokarst lakes of the river catchment (n = 5); circles describe outliers; stars describe extreme outliers.

Abb. 5: „Box-Whisker" Diagramme ausgewählter hydrochemischer Parameter für verschiedene Gewässert. Ox: Altwasserseen (n = 21); poly: Polygonseen (n = 9); Pore: Porenwasser (n = 9); Lena: Lena Flusswasser (n = 18); Therm1 (Th_1): Thermokarstseen der 1. Terrasse (n = 44); Therm3 (Th_3): Thermokarstseen der 3. Terrasse (n = 7); Therm_c (Th_c): Thermokarstseen des Lena-Einzugsgebiets (n = 5); kleine Kreise beschreiben Ausreißer, kleine Sternchen beschreiben extreme Ausreißer.

Thermokarst lakes

Except for Lake 39, these lakes are characterized by low concentrations of TDS (66.9 ±3.45 mg L^{-1}). The maximal value of 134 mg L^{-1} was detected in Lake 26 on Sobo-Sise Island. Among the major ions Ca^{2+}, HCO_3^-, and rarely Mg^{2+} were dominant. Neutral pH values ranged from 7.2 to 7.5. Hydrochemical parameters of thermokarst lakes vary to a larger degree than parameters of other lake types (Cv = 0.39-0.89, Tab. 2).

The variability of major cation, anion, TDS, and some trace element concentrations can be connected to the different geomorphological settings of thermokarst lakes within the delta and outside. The hydrochemical composition of water bodies located on the first terrace of the delta differs from those of water bodies located in other landscape units (on the third geomorphological main terrace of the delta and outside of the delta on different parts of the Lena River catchment).

Concentrations of Si^{4+} in lakes of the first terrace were quite high with particularly large values in thermokarst lakes that are flooded by Lena River waters. Relatively high concentrations of Si^{4+}, which varied from about 0.5 to 1.52 mg L^{-1} and decreased over the summer period, were determined in Lake 5 and Lake 10, while in Lake 7 and Lake 9 concentrations of Si^{4+} exceeded 1.00 mg L^{-1} throughout the summer. Concentrations of Fe^{3+} for most of the lakes did not exceed 0.01 mg L^{-1} but in some Kurungnakh Island lakes (Lake 14, Lake 15, and Lake 16) Fe^{3+} varied from 0.021 to 1.38 mg L^{-1}.

The Box-Whisker plots represent the general tendency for Ca^{2+}, Mg^{2+}, Cl^-, and HCO_3^{2-} of thermokarst lakes of the third geomorphological main terrace to be higher compared to other thermokarst lake subtypes (Fig. 5). However, significant differences ($p < 0.01$) were estimated in concentrations of Cl^-, Na^++K^+, and Sr^{2+} between thermokarst lakes of the first and the third main terraces.

No significant differences were found between thermokarst lakes of the first terrace and lakes of the Lena River catchment. However, the mean lake concentrations of all the major ions, with the exception of Mg^{2+}, are significantly ($p < 0.01$) lower than concentrations found in river water.

Water from Lake 39 is distinguished by a completely different chemical composition. Lake 39 is located close to the delta sea edge at the mouth of the Olenekskaya branch. A single measurement of Lake 39 water shows very high TDS values (633 mg L^{-1}) compared to other investigated thermokarst lakes due to the influence of salt spray from the Laptev Sea. Na^+ and Cl^- dominate among the major ions. The highest concentrations of Sr^{2+} (0.24 mg L^{-1}), B^{3+} (0.064 mg L^{-1}), Br^- (0.97 mg L^{-1}), and Ba^{2+} (0.029 mg L^{-1}) among thermokarst lakes were also measured for Lake 39 (Tab. 2).

Oxbow lakes

The hydrochemical composition of the studied oxbow lake water was characterized by a significantly ($p < 0.01$) higher concentration of TDS (84.1 ±4.58 mg L^{-1}) as well as significantly ($p < 0.01$) higher concentrations of Ca^{2+}, Na^++K^+, Cl^-, SO_4^{2-}, Si^{4+}, and Sr^{2+} compared to thermokarst lake water. Among the major ions Ca^{2+} and HCO_3^{2-}, were dominant. Values of pH were 7.1-7.2. Concentrations of Ba^{2+} (0.15 mg L^{-1}) and Fe^{3+} (0.05 mg L^{-1}) measured in Lake 3 were the highest among all oxbow lakes. Na^++K^+, Cl^-, SO_4^{2-}, and Si^{4+} ions exhibited high variances.

There are no significant differences between the Lena River water and oxbow lake water mean concentrations of Mg^{2+} and Cl^-, whereas concentrations of other major ions and also Si^{4+} and Sr^{2+} are lower in oxbow lake water than in river water.

At the beginning of the summer the concentration of Si^{4+} was 0.51 mg L^{-1} in Lake 1, 1.0 mg L^{-1} in Lake 20, 1.35 mg L^{-1} in Lake 2 and 1.83 mg L^{-1} in Lake 3 and then decreased over the summer period.

Polygonal ponds

Individual polygonal ponds, and also a lake formed of coalesced polygonal ponds are characterized by the lowest concentration range of TDS (66.2 ±6.57 mg L^{-1}) compared to the other lake types. Among the major ions Mg^{2+} or Ca^{2+} and HCO_3 were dominant. There were no significant differences in the mean concentrations of investigated hydrochemical characteristics between thermokarst lakes of the first terrace and polygonal ponds.

Box-Whisker plots (Fig. 5) show that variability and medians of Na^++K^+, Cl^-, and SO_4^{2-} in polygonal ponds are similar to those in pore water samples. Statistical analysis also shows that there are no significant differences in mean concentrations of the major ions and TDS between pore waters and polygonal pond water, but concentrations of Si^{4+} and Sr^{2+} in pore waters are significantly higher ($p < 0.01$).

Polygonal ponds are sensitive to the impact of active layer pore water which contributes a significant volume of water relative to the small volume of the ponds. For example, Fe^{3+} is actively released from tundra landscape soils; Fe^{3+} concentration was relatively high in the water of small polygonal ponds (Lake 6 and Lake 12), varying from 0.16 to 0.60 mg L^{-1}, but Fe^{3+} concentration in pore waters reached 2.79 mg L^{-1}. The small polygonal pond pH varied from 6.2 to 6.5 and was characterized by slightly acidic values which is attributed to the active layer pore water source (pH = 5.6-6.2).

Lagoon lake

A single measurement of water chemistry in Lake 38 shows completely different chemical composition compared to other investigated delta lakes, but Lake 38 is similar to Lake 39. Lake 38 water was characterized by high TDS (1,300 mg L^{-1}) and dominant Na^+ and Cl^- among major ions. Concentrations of Sr^{2+} and Br^- reached their maximum values among investigated lakes (Tab. 2).

DISCUSSION

Hydrological characteristics of studied lakes

The hydrological and hydrochemical characteristics of the studied lakes in the downstream part and in the delta of the Lena River investigated in summer season are comparable to those for other Arctic regions. Lake-thermokarst relief is a prominent feature of the Lena River delta. Similar morphometric lake parameters are typical for thermokarst regions of central and eastern Siberia (Duff et al. 1999, Laing et al. 1999, Laing & Smol 2003), western Siberia (Pokrovsky et al. 2014), and the Mackenzie delta region (Lim et al. 2001). Typical thermokarst landscape lakes in a zone of continuous permafrost are generally small and shallow; thermokarst formation processes prevail in these lakes (Kumke et al. 2007). However, our study indicates that the investigated lakes in the Lena River delta experience different environmental conditions and were formed as a result of various causes. The studied lakes are characterized by differences in morphometric parameters (size, shape, depth) and in origin, and they vary from small, shallow, separate polygonal ponds to bigger and deeper thermokarst, oxbow, and lagoon lakes. Nevertheless, thermokarst processes exert a significant influence on the formation and/or development of all types of Lena River delta-lakes.

Due to the lower elevation of the Holocene river delta terrace relative to the river level there is a high probability of lakes flooded during annual spring floods, or due to rising water levels during rainfalls and storms in the catchment. Within the first terrace, the time when river and lake waters interact, as well as the periodicity of flooding, can vary, but some of the thermokarst and oxbow lakes of the delta found on the first river terrace are flooded in spring by the river.

Some of the oxbow lakes e.g. Lake 2, are characterized by the development of thermokarst processes. Additionally, one of the studied lakes (Lake 38), characterized as a lagoon lake strongly affected by seawater, also formed as a result of thermokarst processes and subsequent coastal erosion. This mechanism of formation and the current state of the Arga Island lagoon lakes are described in detail in Are & Reimnitz (2000).

Hydrochemical characteristics of studied lakes

TDS values detected in thermokarst lake water in this study ranged from 20.8 to 134 mg L^{-1} and are similar to those reported for previous studies in the Lena River delta (Duff et al. 1999), but are lower than those reported in studies from Arctic Canada (e.g., Hamilton et al. 2001, Lim et al. 2001), central Yakutia (Kumke et al. 2007), and the Mackenzie Delta where higher concentrations of TDS and the major ions in lake water were attributed to thermokarst slumping (Kokelj et al. 2005). The dominance of Ca^{2+}, Mg^{2+}, and HCO_3^- and low TDS in lake water from the Lena River delta is attributed to the prevalence of meteoric waters among the other water sources; Ca^{2+}, Mg^{2+}, and SO_4^{2-} dominate in lake water from the Mackenzie Delta.

Negligible concentrations of minor and trace elements are a feature of the studied lakes because these water bodies are located in areas affected by continuous permafrost and are isolated from the mineral-rich horizons. However, relatively high concentrations of Si^{4+}, Sr^{2+}, and Fe^{3+} are distinctive features of the region associated with the geological structure and climatic conditions of the territory.

The hydrochemical composition of Lake 37 (Kutyunda Lake) and Lake 36 (Elgene-Kuele Lake) that we found is similar to that reported by Biskaborn et al. (2013, 2016) and Schleusner et al. (2015) for 2009 and 2010.

Additionally, lakes of the delta that are located close to the coastal zone are characterized by marine influence. Marine influence in the case of lakes located several tens of kilometres from the seacoast (i.e. Lake 39) is associated with aerosol transport. The hydrochemical regimes of lagoon lakes separated from the sea by spits (i.e. Lake 38) are controlled by wind-driven storm surges (Are & Reimnitz 2000); this is similar to coastal sites in the Canadian high Arctic (Lim et al. 2001), where dominance is shifted to Na^+ and Cl^- ions.

Thermokarst lake waters show pH values comparable to those measured by Duff et al. (1999) for the Lena River delta, very similar to pH measured in lakes located in western Siberian continuous permafrost. However, in the Lena River delta region pH is generally lower than in lakes of Central Yakutia (Kumke et al. 2007, Wetterich et al. 2008a) and is significantly higher than in the surface waters of western Siberian palsa acidic peat (Pokrovsky et al. 2014). These and other differences in hydrochemical parameters between regions reflect the environmental conditions of the territories and might be affected by differences in natural processes and vegetation composition in the lake catchment area, i.e. the presence and decomposition stage of peat in the lake catchment.

Natural processes in lake catchments lead to specific hydrochemical characteristics of the Lena delta-lakes. Degradation of active layer organic matter during the warm period leads to the release of humic acids into pore water, and soil fluxes decrease lake water pH values during summer season. Release of chemical elements from the active layer in the Lena River delta explains increased concentrations of Si^{4+} and Fe^{3+} in pore water. Thus, the influence of the catchment area most affects lakes with small water volume, especially small polygonal ponds, where the percentage of water coming from active layer pore water is more significant.

Where hydrological connections exist between water bodies and river water, the hydrochemical composition of the river also influences lake water chemistry. Thus, chemical characteristics of oxbow lakes, which occur on the first river terrace, differ from those of water bodies of other origins located in other landscape units at higher elevations. Oxbow lake water is characterized by higher values of TDS and some of the major and trace ions compared to unflooded thermokarst lakes. The study of Schneider et al. (2016), however, indicates that water from flooded lakes in the Indigirka Lowland is characterized by rather different chemical composition than water from the Lena River, and by lower electrical conductivity compared to unflooded lakes due to dilution with river water. Several thermokarst lakes of the first Lena delta terrace are influenced by river water and are characterized by higher concentrations of Na^+, Cl^-, Si^{4+}, and Sr^{2+}; these ions actively migrate with the river water.

The specific water chemistry of polygonal ponds can be explained by the fact that active layer thaw waters are a significant source of chemical elements for this type of lake due to their relatively small volume. Mg^{2+} often dominates among the major cations, and concentrations of Na^{+}+K^{+}, Cl^{-}, SO_4^{2-}, and Fe^{3+} are similar to those in pore water samples due to release of these elements from permafrost (Kokelj et al. 2005). Polygonal pond pH values are similar to the slightly acidic to circumneutral pH values found in Indigirka lowland water (Schneider et al. 2016)

CONCLUSION

This study revealed significant differences between the hydrological and hydrochemical characteristics of the studied lake types in the Lena River delta and in the lower Lena River catchment. These differences can be explained by differences in the lakes' formation processes, resulting morphometric parameters, the intensity of permafrost and thermokarst processes in their watersheds, and hydrological connections determined by their location in the relief, i.e. elevations of the lakes relative to the river water level (location on a geomorphologic terrace) as well as marine influence. In particular, we found the following patterns:

1) Thermokarst lakes of the Holocene river terrace that are flooded during the spring freshet are characterized by higher concentrations of Si^{4+} at the beginning of the summer period, when the spring freshet has passed.

2) Thermokarst lakes of the third geomorphological main terrace are characterized by higher concentrations of Na^{+}, Cl^{-}, and Sr^{2+} compared to thermokarst lakes of the Holocene river terrace and the Lena catchment. This may be due to enhanced interaction of lake water with mineral horizons because thermokarst lakes on the third geomorphological main terrace are deeper than thermokarst lakes on other levels.

3) Polygonal ponds and a lake of coalesced polygons are characterized by lower concentrations of TDS and pH values but a higher concentration of Fe^{3+} compared to the other lake types; this is explained by the significantly larger contribution of water from the active layer feeding the small volume of these water bodies, and their small watersheds in comparison with other lake types.

4) Oxbow lakes are characterized by higher concentrations of TDS and dissolved Ca^{2+}, Na^{+}+K^{+}, Cl^{-}, SO_4^{2-}, Si^{4+}, and Sr^{2+}. This can be explained by enrichment of lake waters by river waters with significantly higher concentrations of these elements.

5) Lakes located near the sea in the estuaries and on the coast, are affected by seawater via aerosol transport and by storm surges into coastal lakes or lagoons which is evidenced by higher concentrations of TDS as well as of Na^{+} and Cl^{-}, and Na^{+} and Cl^{-} dominate the chemical composition of lake water.

6) Negligible concentrations of minor and trace elements are a feature of all the studied lakes because water bodies in areas with continuous permafrost are isolated from the mineral horizons. However, relatively high concentrations of Si^{4+}, Sr^{2+}, and Fe^{3+} are distinctive features of the regional background.

The small size of the lakes and their location in the Arctic permafrost region with severe northern climate conditions make these water bodies vulnerable to external factors, e.g. climatic changes and human impact. The consequences of climate change, including river water level rise, changes in precipitation, and degradation of the permafrost landscape can force dramatic changes in lake hydrological and hydrochemical parameters.

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